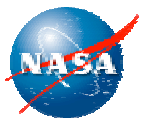


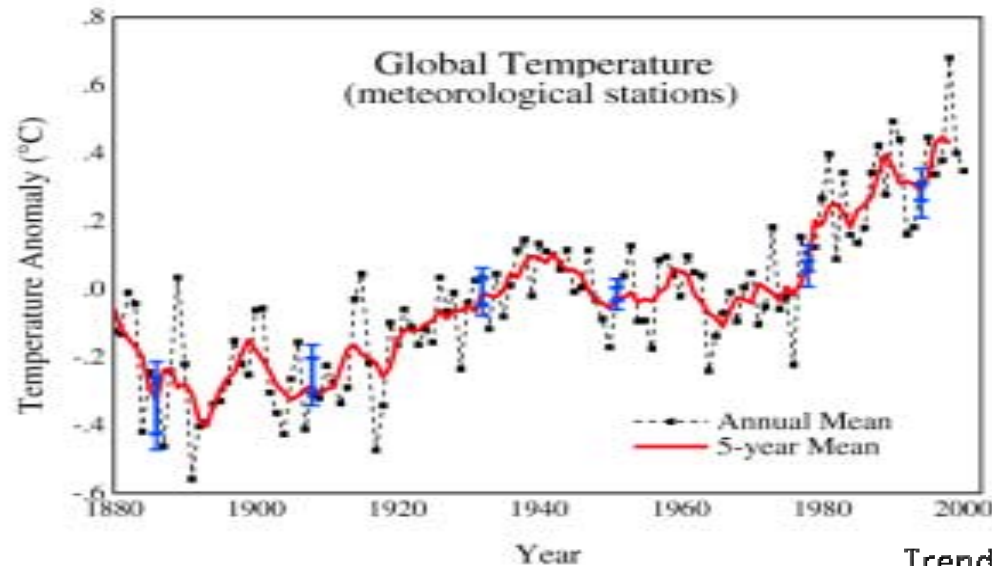
GEO HYPERSENSPECTRAL MISSION FOR LAND AND OCEAN CARBON AND WATER CYCLE

Janette C. Gervin, Jaime Esper, Charles R. McClain, Forrest G. Hall, Elizabeth M. Middleton, Watson W. Gregg, Antonio Mannino, Robert G. Knox, Philip W. Dabney, K. Fred Huemmrich, H. John Wood, Michael Roberto

NASA Goddard Space Flight Center, Greenbelt, MD 20771

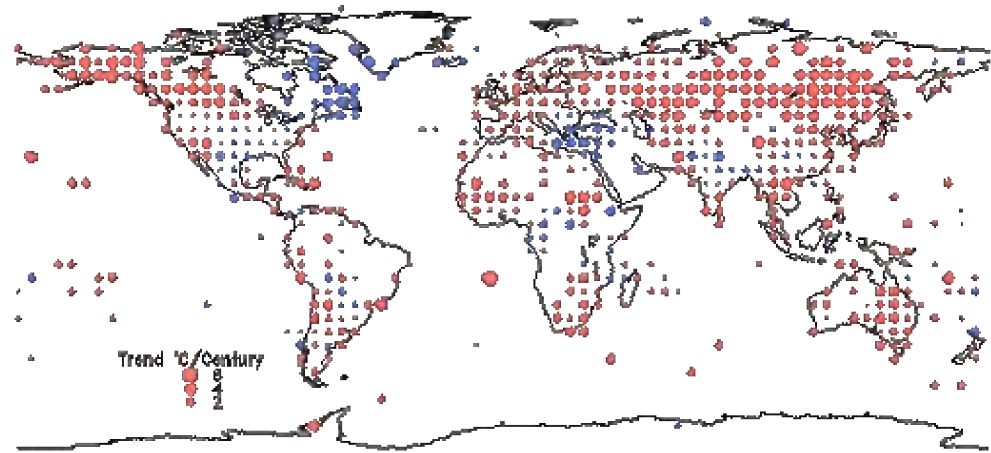


The Earth Is Warming



Weather station records and ship-based observations indicate that global mean surface air temperature warmed between about 0.4 and 0.8 °C (0.7 and 1.5 °F) during the 20th century.

Trends of surface temperature (1951–1993)
Global Historical Climate Network (GHCN)





What Drives Change in the Climate System?

Earth's Heat Balance = **Warming** - **Cooling**

Warming:

Greenhouse gases
Absorbing aerosols

Greenhouse Gases

- Carbon dioxide CO_2
- Methane CH_4
- Water Vapor H_2O
- Nitrous Oxide N_2O
- Chloroflurocarbons CFC's
- Ozone O_3

Absorbing Aerosols

- Smoke
- Soot

Cooling:

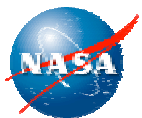
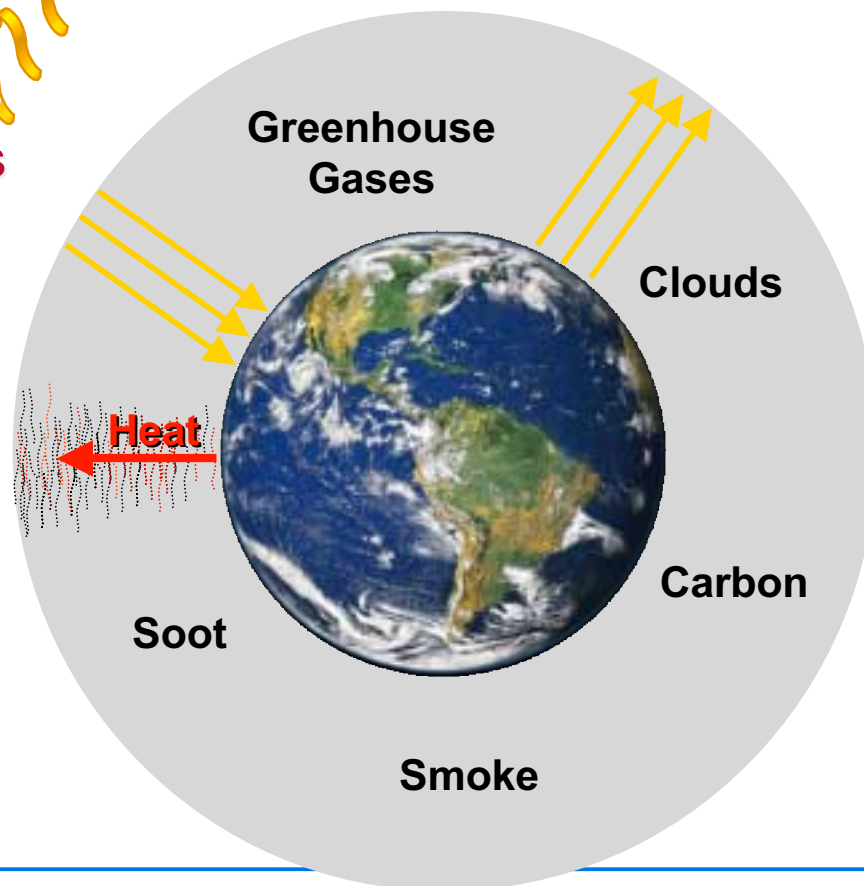
Reflective aerosols
Natural carbon sequestration

Reflective Aerosols

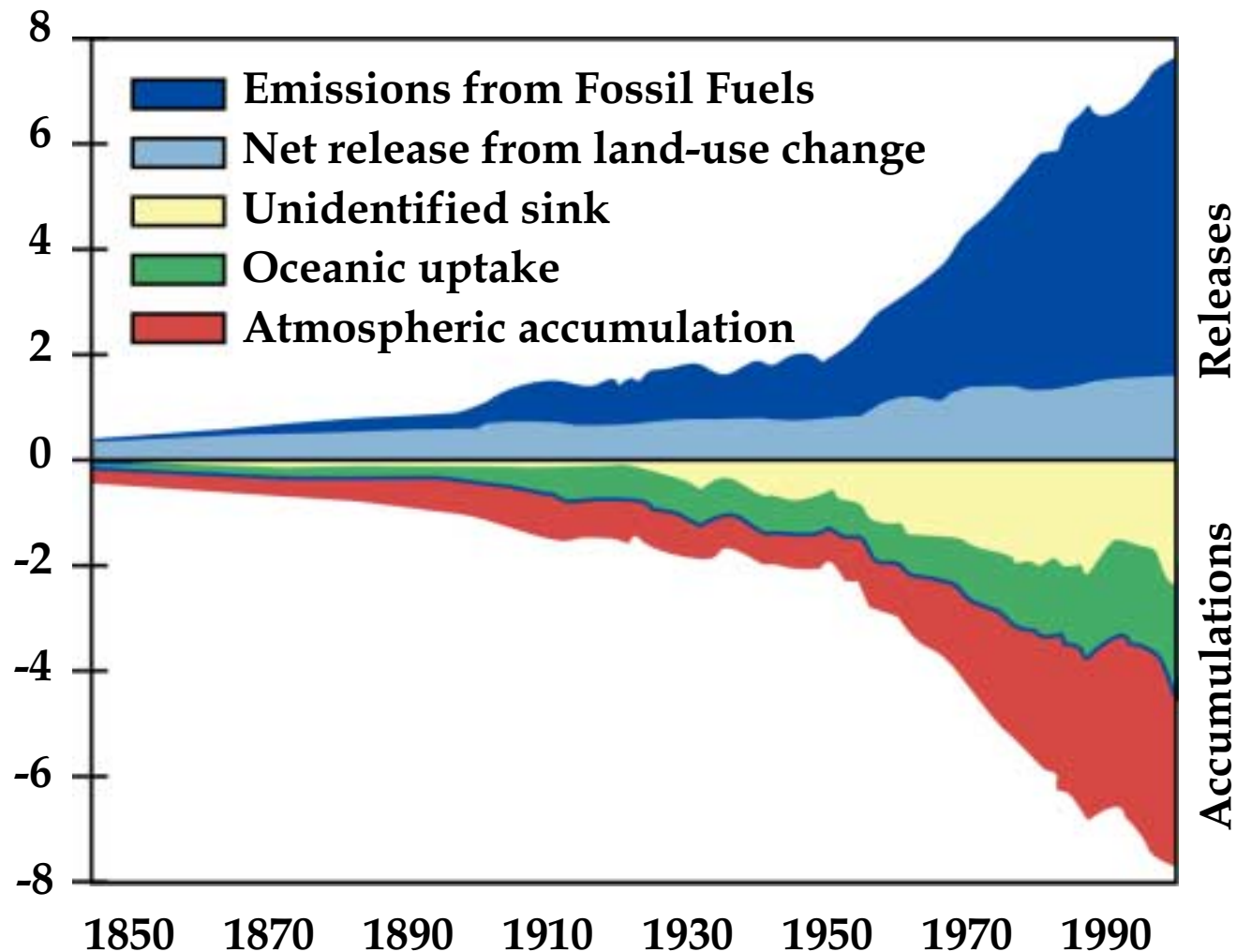
- Impact on cloud formation
- Dust
- Volcanic aerosols SO_2

Natural carbon sequestration

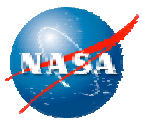
- Forests/Soils
- Air-sea CO_2 equilibrium
- Ocean Biota



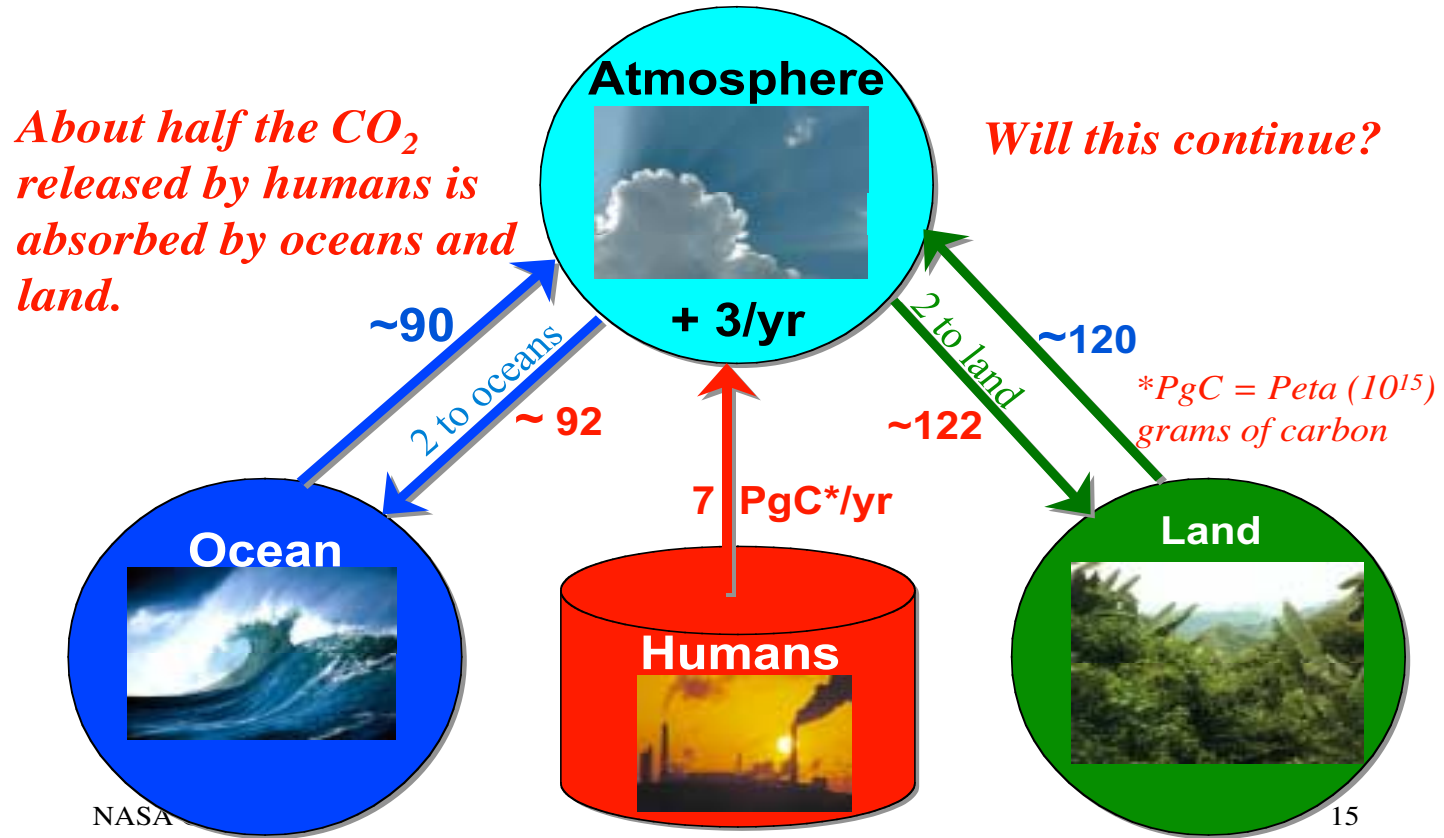
Net Flux of Carbon (Pg C/yr)



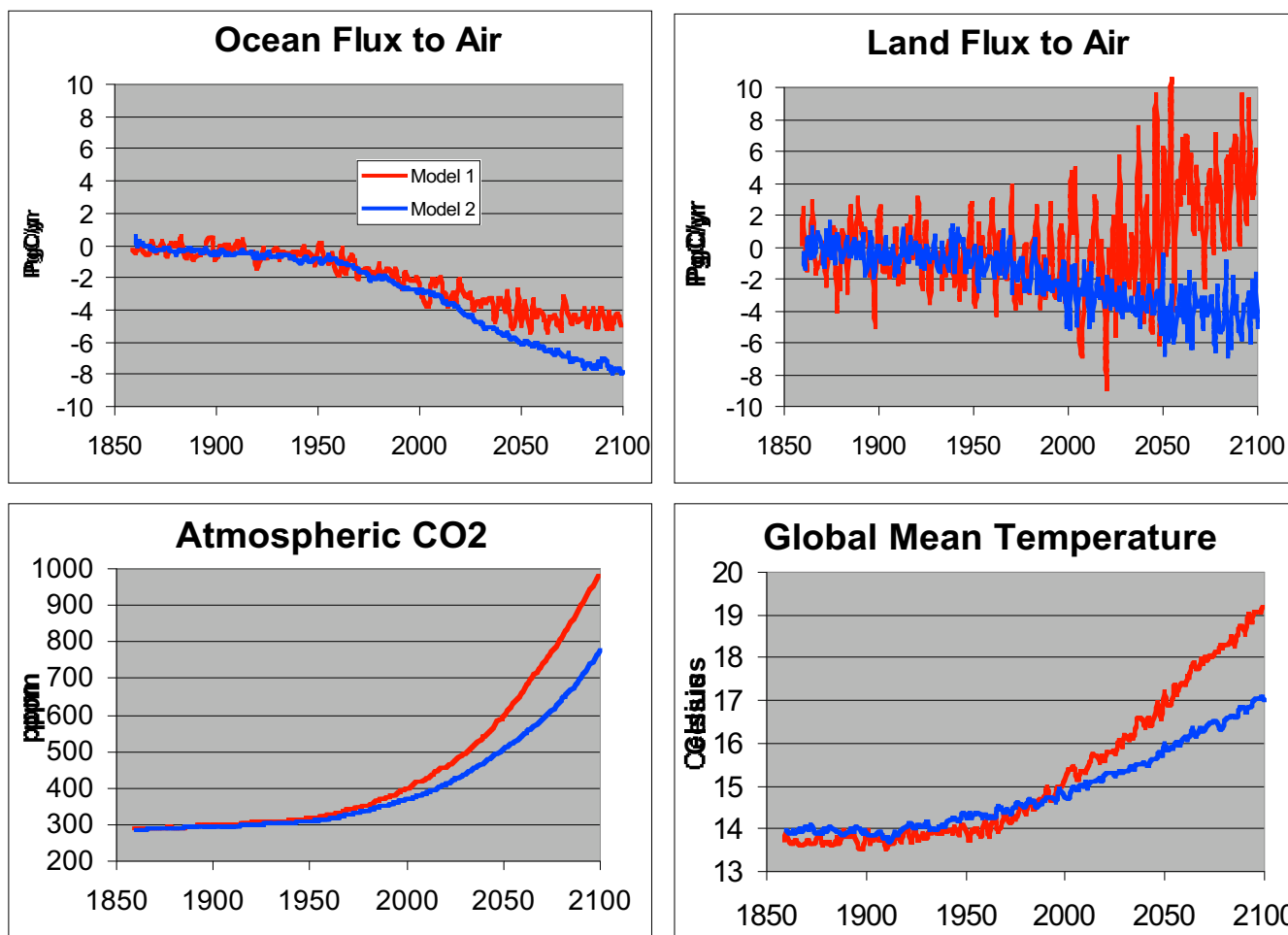
source: WHRC



The Global Carbon Cycle



Uncertain Futures



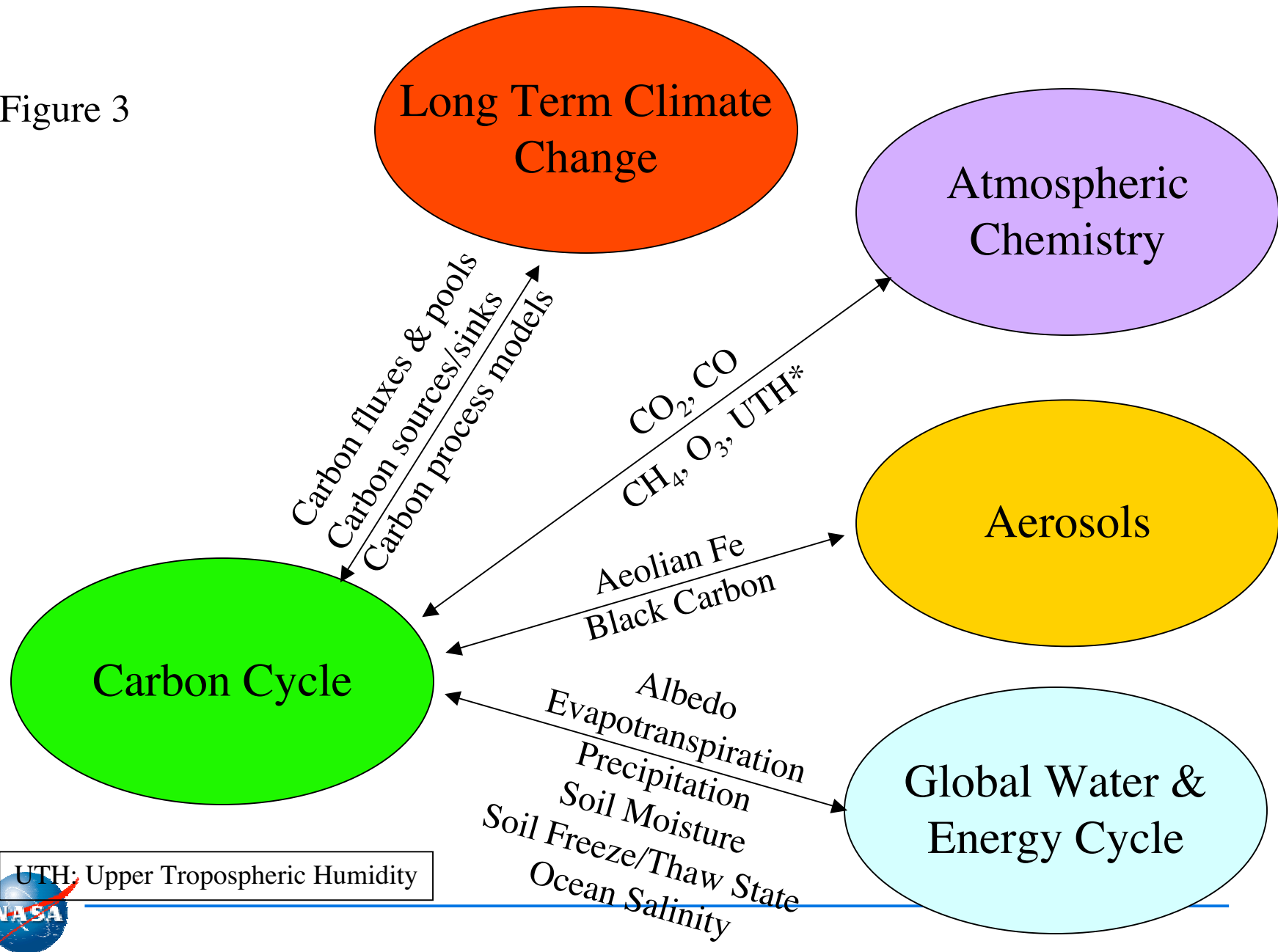
As CO₂ emissions have increased, the land and oceans have absorbed more and more carbon. Projections of future CO₂ levels depend on our knowledge of the biosphere and how it interacts with climate. Given identical human emissions, different models project dramatically different futures.



Which is correct? How can we know?

Code 900 Theme Connections

Figure 3



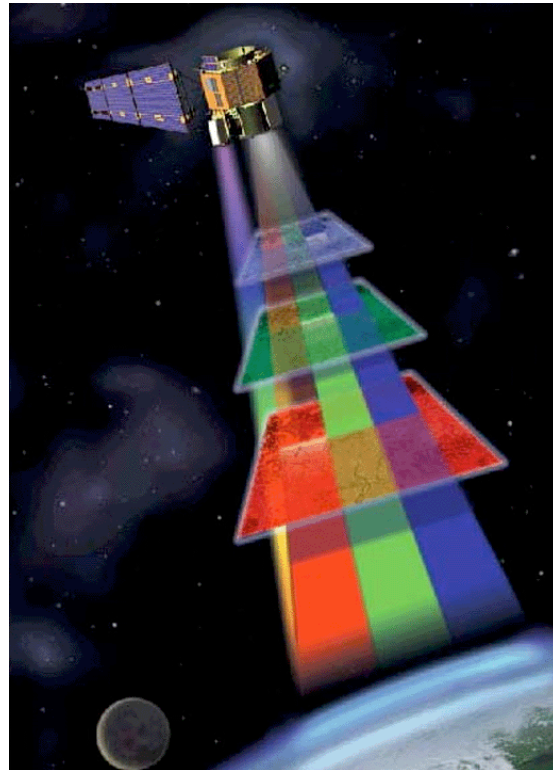
Critical Gaps

- **MISSING:**
 - Global time series of CO₂ atmosphere-surface exchange.
- **MISSING:**
 - Ecosystem carbon storage due to biomass and its change.
 - Carbon consequences of disturbance.
- **MISSING:**
 - Measurements of critical biochemicals mediating global ocean surface layer uptake and export of carbon.
 - Models of air-sea CO₂ exchange.
- **SOLUTION:**
 - Design and launch satellite to measure column and profile CO₂.
 - Develop and use data assimilation techniques to generate surface flux fields.
- **SOLUTION:**
 - Design and launch satellite to measure biomass and its change.
 - Process on-orbit satellite data to map disturbance and recovery.
- **SOLUTION:**
 - Develop satellite sensor to measure organic and inorganic compounds and models to compute carbon uptake.
 - Develop exchange process models.

SUPPORTED BY FIELD CAMPAIGNS, CALIBRATION/VALIDATION EFFORTS, MODEL DEVELOPMENT AND DATA ASSIMILATION RESEARCH TO FULLY UTILIZE SATELLITE OBSERVATIONS.

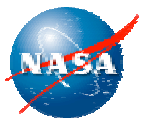


LEO Missions Implementation: Low-Medium Density Biomass and Coastal Ocean

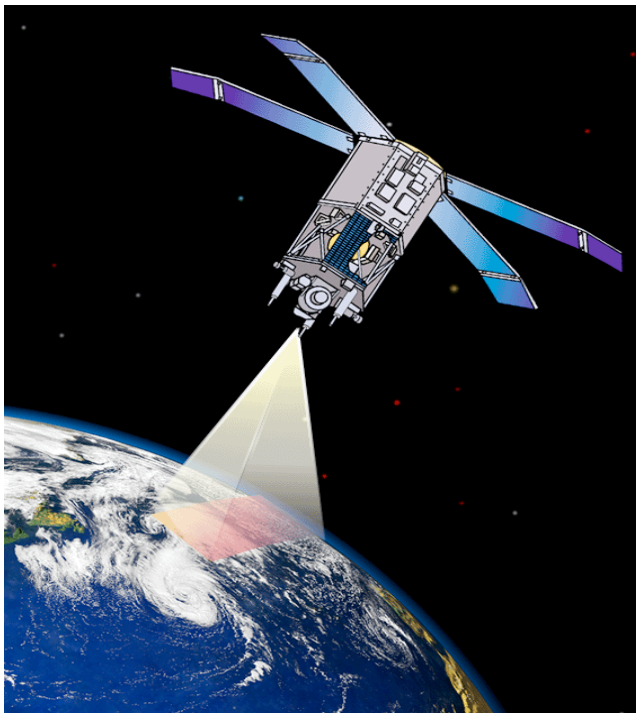


Mission Life: 5 Years
Orbit: 705 km circular sun-synchronous with a 10:30 a.m. descending node
Space Access: Taurus or equivalent class launch vehicle

Key Technologies:
Large area focal plane arrays, large capacity on-board recorders, and high rate downlink systems for improved mission performance



LEO Missions Implementation: Global Ocean Carbon



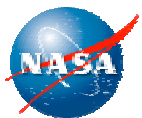
Mission Life: 5 Years

Orbit: 705 km polar, sun-synchronous, with a 12:00 noon crossing time

Space Access: Pegasus XL or equivalent class launch vehicle

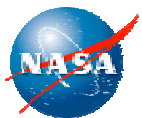
Mission Options: A single instrument mission

Key Technologies: selection of bands not generally used in land applications, improvements in sensor design, and the use of onboard data processing to optimize data retrieval



Transition to Geosynchronous

- Carbon study also defined land vegetation productivity as a high priority.
 - Requires diurnal coverage
 - Requires 5 to 10 nm spectral resolution - 100 m spatial resolution
- GEO was recognized to be a better platform for most carbon cycle requirements. Could also accomplish most science proposed from LEO (e.g. low density biomass)
- However, technology readiness of hyperspectral from GEO uncertain.
- Now GEO more attractive than before
 - Technology advancements in hyperspectral
 - Telescopes and detectors
 - Focal planes
 - NASA focus on new frontiers



Science Objectives

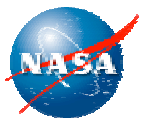
Land

Improved observations of Terrestrial biomes are required:

To improve the seasonal and annual estimates of regional productivity, expressed as Net Ecosystem CO₂ Exchange (NEE) over regions 1000 km² to within 0.25 Petagrams / year.

Oceans

High temporal observations of ocean color (primary productivity, biomass, CDOM, etc.) to resolve diurnal variability and detect bias.



Science Goals and Rationale

- Land

- To develop a satellite sensor to directly measure the photosynthetic control of diurnal, land surface-atmosphere carbon and water exchange
 - Photosynthetic rate (P_c) = Absorbed PAR x Light Use Efficiency
(Existing Sensors) (New Sensor)
 - Evapotranspiration = $P_c \times (h/c)$
 - Obviate the need for difficult to measure parameters such as surface temperature, soil moisture, vapor pressure.

- Ocean

- To develop satellite sensor to measure surface ocean organic and inorganic compounds
 - Carbon Pools (e.g., particulate & dissolved organic carbon)
 - Terrestrial Carbon Discharge to Coastal Ocean
 - Model Parameter Inputs & Validation (e.g., primary production)



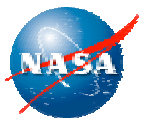
Key Measurement Objectives

Land

- Assess the influence of climate change on terrestrial productivity by studying the dependence of processes underlying terrestrial carbon uptake, storage, and release on external influences.

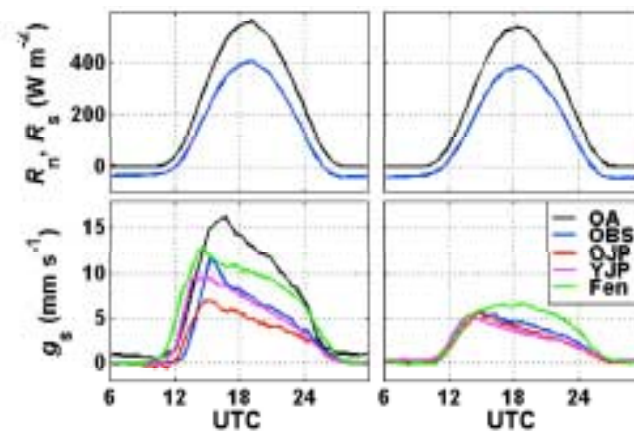
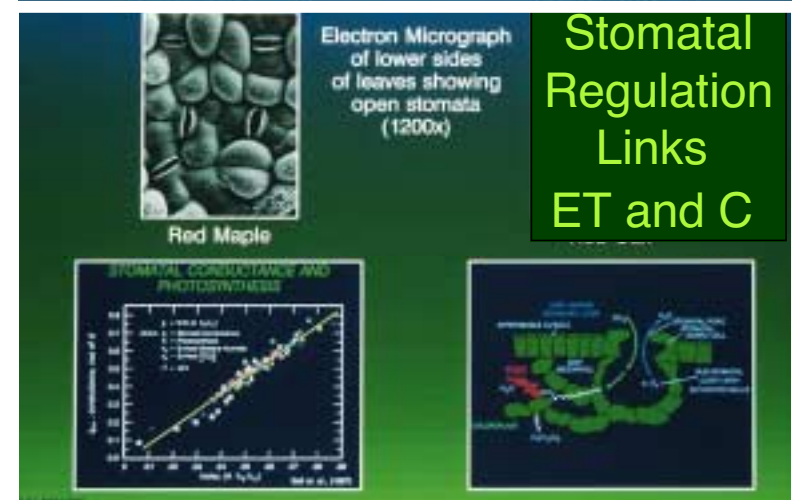
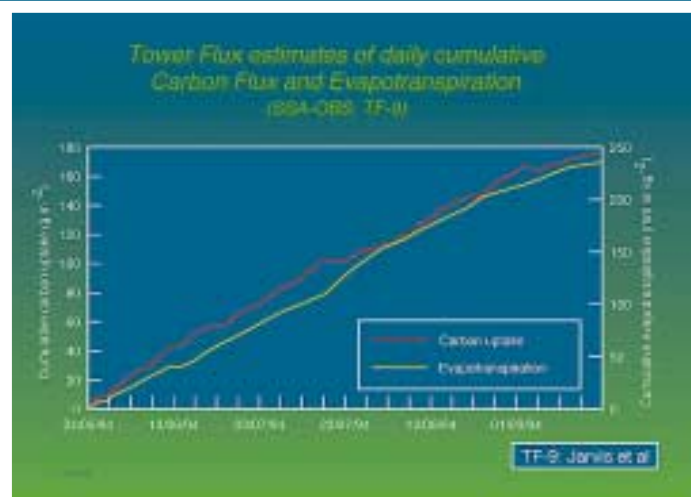
Oceans

- Establish the interaction between the solubility and biological pumps for CO₂ with the required spatial and temporal resolution, and apply at global scales to determine their role in climate change.



Diurnal Variation in Atmosphere-Surface Mass/Energy Exchange is a Key Process in Carbon and Water Cycling

Carbon Uptake C
Evapotranspiration E

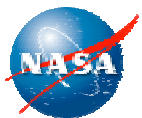
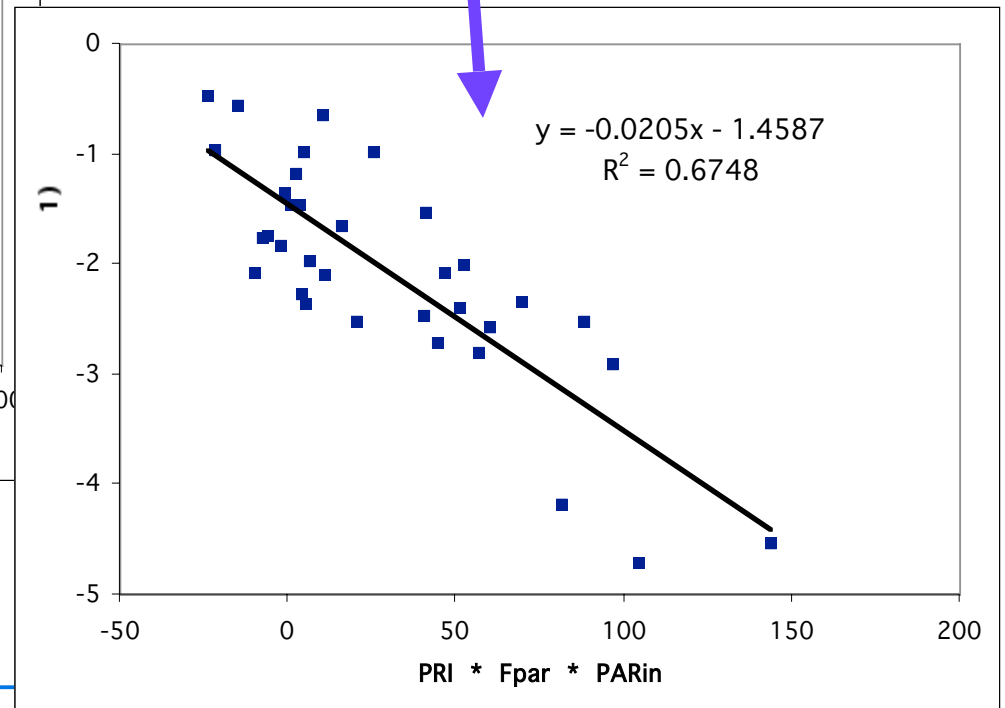
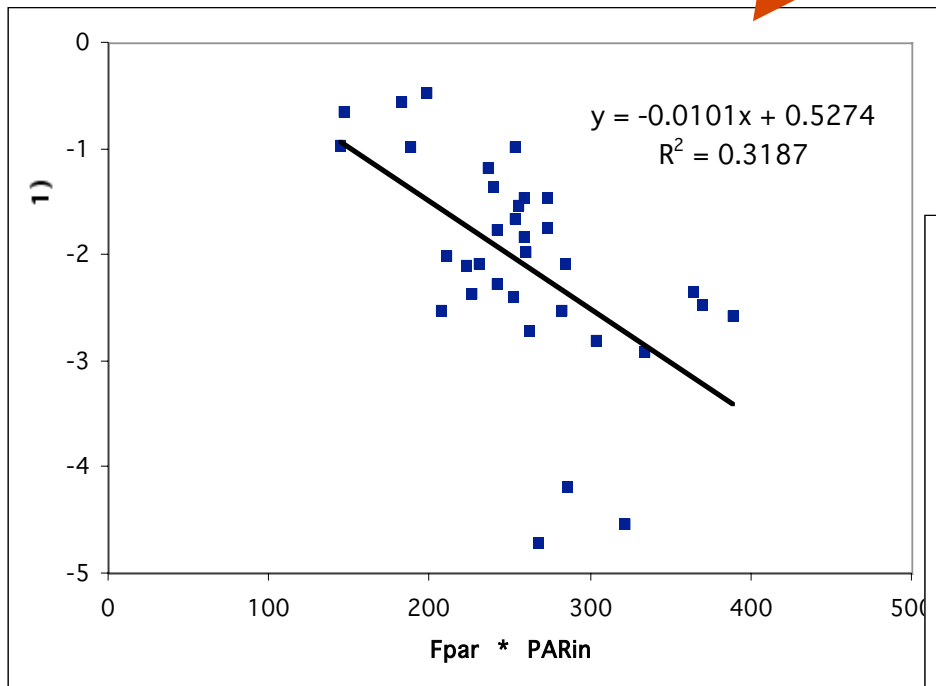


Stomata open
in response to light.

Stomata close in response to
moisture stress, excess leaf
temperature, and low humidity.

LAND SCIENCE RATIONALE

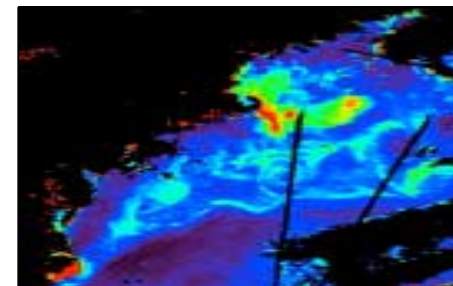
Photosynthetic rate (P_c) = Absorbed PAR x Light Use Efficiency
(Existing Sensors) (New Sensor)



Coastal & Ocean Science Requirements

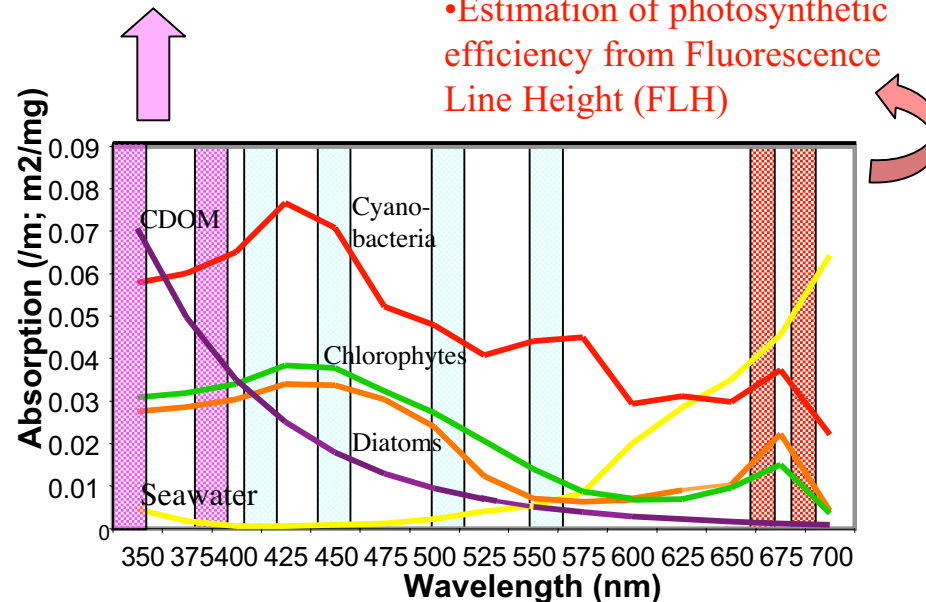
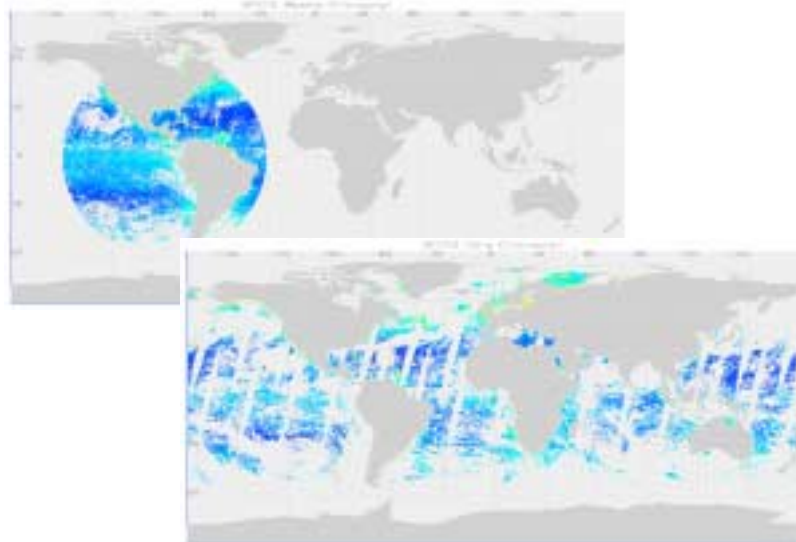
VIIRS will not have the spectral bands in the UV or for FLH.

- Discrimination of terrestrial and open ocean dissolved organic matter (DOC)
- UV effects on marine photosynthesis
- Aeolian iron detection/quantification

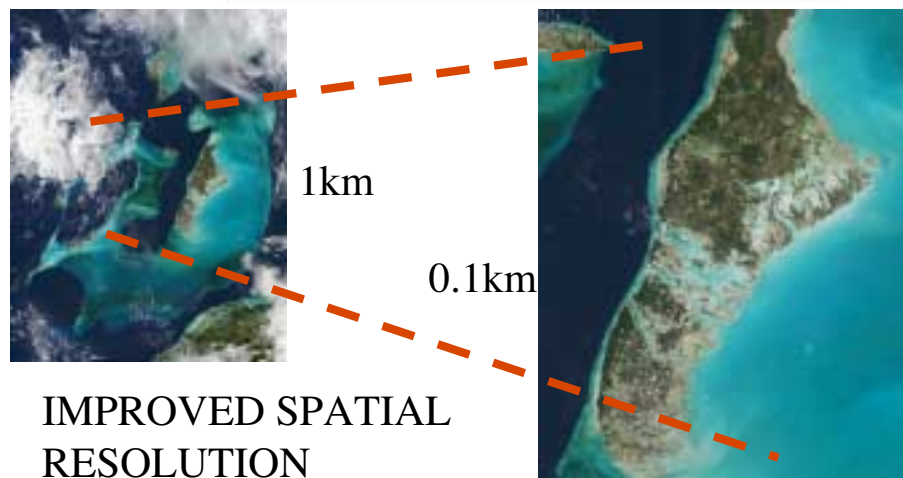


- Estimation of photosynthetic efficiency from Fluorescence Line Height (FLH)

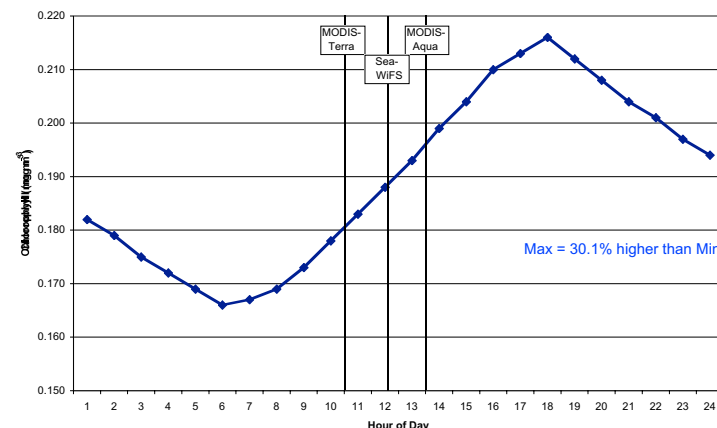
IMPROVED DAILY REGIONAL COVERAGE



IMPROVED SPECTRAL & TEMPORAL COVERAGE

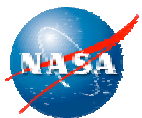


Diurnal Variability in the North Indian Ocean



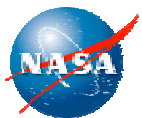
“A Fork in the Road”

- Narrow Bands in atmospheric windows, with broadband aerosol/atmospheric correction
(e.g., MODIS surface reflectance products)
- Hyperspectral with enough fidelity to both
 - do atmospheric correction and
 - resolve vegetation spectral features
(e.g., derivative spectra)



Combined Mission

- Address the original science requirements, while increasing the scientific return of a single spacecraft.
- Renewed interest in advanced measurement capabilities from geostationary altitudes, particularly hyperspectral measurements.



Ongoing GSFC Study of a Combined GEO Hyperspectral Mission

- Address the original science requirements, while increasing the scientific return of a single spacecraft.
- Renewed interest in advanced measurement capabilities from geostationary altitudes, particularly hyperspectral measurements.
- New emphasis on **light-use efficiency** and ecosystem carbon exchange.
- Full diurnal coverage, hemispheric or near-global
- Single spacecraft, near geostationary, or LEO constellation.



Scientific Measurement Requirements: Input from Science Working Group

Spectral

Land

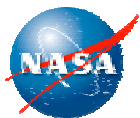
High resolution spectra (≥ 400 continuous bands) in VIS and NIR; augmented by select narrow infrared bands, 1500-2400 nm.

1. Capability to distinguish land cover types using the IGBP classification.
2. Capability to derive a photosynthetic efficiency factor from spectra (LUE).
3. Capability to determine monthly rates of productivity for various classes of forests, grasslands, wetlands, & agriculture (as C or biomass in $\text{kg/m}^2/\text{mo}$).

Oceans

Optical Range 340-1000 nm

Spectral resolution ≤ 2 nm



Scientific Measurement Requirements Con't

Spatial

1. Capability to monitor ecologically relevant vegetation patches:
 - * track habitat loss due to human activity.
 - * track ecosystem change due to climate changes & pollution load.
2. Capability to Intensively monitor temperate and equatorial regions of the Western Hemisphere.
3. Capability to frequently monitor land regions globally.

Temporal Cycles

1. Capability for diurnal, relatively cloud-free, observations of vegetation physiological status.
2. Capability to determine the true dates and/or duration of physiological events affecting photosynthetic function, per annual cycle.



Instrument Functional and Performance Requirements

Spectral Parameters

Functional Requirement:

1. High resolution spectra (≥ 400 continuous bands) in VIS and NIR; augmented by select narrow infrared bands, 1500-2400 nm.
2. Spectral Priorities:
 - * Photochemically Active Regions, All bands, 400-750 nm
 - * Selected Bands from NIR plateau
 - * Selected Bands, IR associated with Veg. Spectral Features
 - * Atmospheric Bands, aerosols
 - * Atmospheric Bands, Cirrus Clouds
 - * Atmospheric Bands, 4-5 H₂O
 - * PAR, broadband (thermal band desired)
3. High SNR & absolute radiometric accuracy.
4. Capability to compute derivative spectra without distortions in spectra due to data compressions



Spectral Parameters Con't

Performance Requirement:

Optical Range 400-2400 nm

Spectral resolution: VIS, ≤ 5 nm (2 nm wide); NIR, 5-10 nm (5 nm);
IR, 5-10 nm (5 nm).

Sensor heritage: Upgraded EO-1 Hyperion; GeoSpec

Downlink all bands, 400-750 nm

2-5, 800-1300 nm

1450, 1670, 1820, 1920, 2220 nm (± 3 nm)

O₂A band, 758-772 nm, 2-5 nm wide

1380 nm, 2-30 nm wide

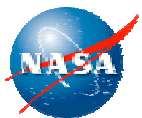
900-980 nm, 2-5 nm wide

400-700 nm (TBD)

SNR $> 500:1$ (1000:1 desired)

$\pm 5\%$ ($\pm 3\%$ desired)

High volume data storage and/or transmission; full spectra
provided on predetermined schedule.



Instrument Functional and Performance Requirements

Spatial

1. Relatively high spatial resolution [Landsat < S < MODIS, VIERS] for typical patch sizes in temperate and coastal areas [High spatial resolution needed for tropical disturbance].
 ≤ 100 m at nadir (≤ 30 m, tropical disturbance)
 ≤ 120 m at oblique (≤ 60 m)
2. Wide field of regard for maximum coverage, but with as small a footprint as possible. Location Accuracy: ≤ 25 m (≤ 10 m)

3. Minimum Coverage Area:

Phase 1 [Geostationary]: N/S America ± 50 degrees latitude (± 60 deg)

Provides diurnal coverage. (Scan every 1-2 hours during daylight hours with fixed viewing geometry), over Western Hemisphere.

Phase 2 [Drifting circumglobally]: ± 50 degrees latitude

(-40 to +65 degrees latitude, summers)

Provides diurnal observations with 2 day overlap on weekly basis for global coverage (Scan every 1-2 hours during daylight hours with variable viewing geometry), with emphasis on growing season.



Instrument Functional and Performance Requirements

Temporal Cycles

1. Repeat observations daily at fixed VA per pixel along swath.
2. Repeat observations daily for 2/3 consecutive days @ variable VA.
3. Optimal view times: diurnals
4. Per Annual Cycle:
 - a) **Dates** of greenup & greendown; maximum greenness; onset of visible stress due to drought, heat, nutrients, etc.
 - b) **Duration** of photosynthetically active period per year (ie.g., peak greenness).

Mission Duration: 4-6 years

Mission Periods:

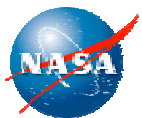
Phase 1: First 12-24 month period

Phase 2: Second 12-24 month period

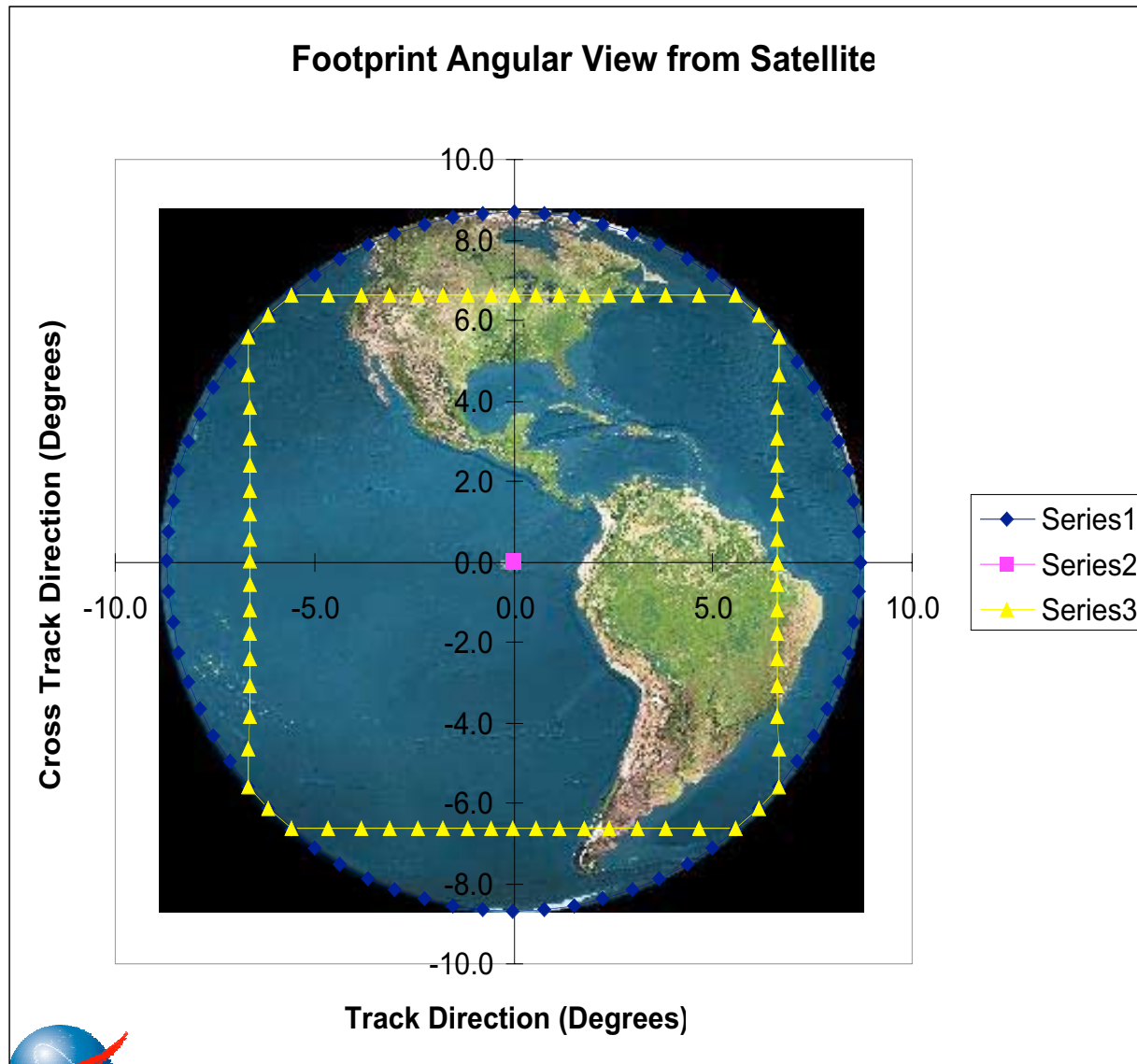


ISAL Study Objectives

- **1st order assessment of SNR and Aperture Size**
 - Developed approach based on customer suggestions for science trades based on priority inputs from the science team
 - Priorities:
 - 1.Temporal Frequency/Diurnal coverage
 - 2.Spectral Resolution / Band Coverage
 - 3.SNR
 - 4.Areal Coverage
 - 5.GSD
 - Secondary evaluation of design input parameters
- **Evaluate design options as time allows for tall poles based on selected instrument parameters for a hyperspectral instrument**
 - Detector Strategies
 - Optical Design
 - Mechanical Strategies
 - Electrical Design



Coverage for 40 degree Elevation



Series 1 = Earth's limb from Geo, equals 8.71 degrees radius.

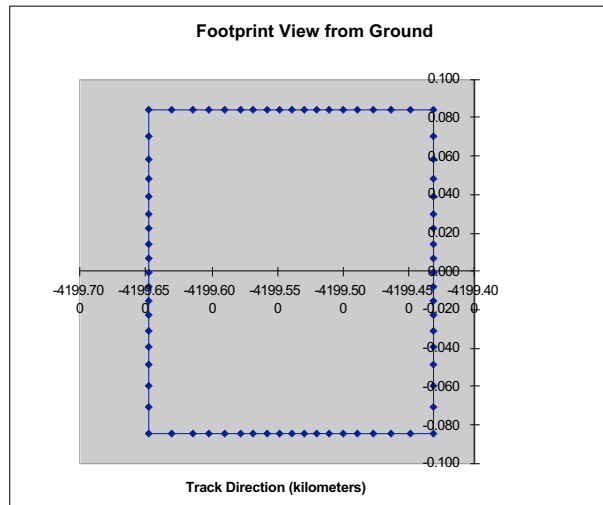
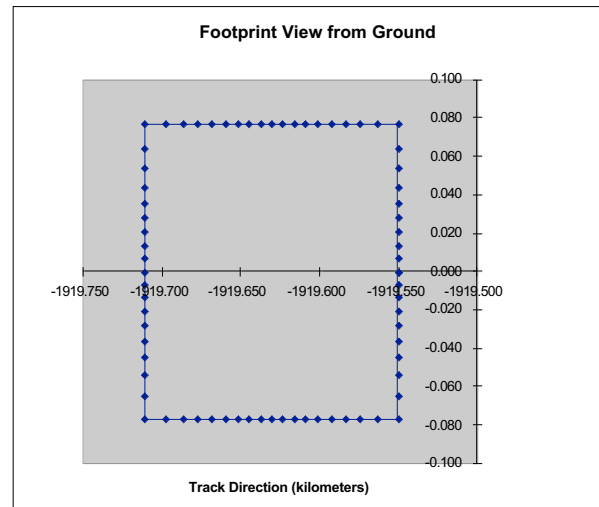
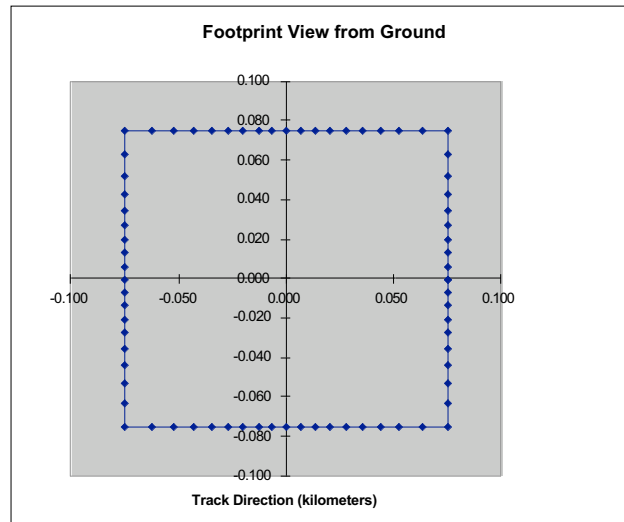
Series 2 = nadir point

Series 3 = coverage for square field from S/C extending 6.65 degrees in each direction from nadir

Revised on Feb 24, 2004



Pixel Footprints



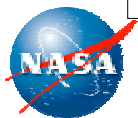
Footprints at 0, 3, and 6 degrees off nadir.

Image Size:

Nadir 150 x 150 meters

3 degrees off nadir 154 x 162 meters

6 degrees off nadir 168 x 217 meters



SNR Performance

- Effective resolution constrained by SNR requirements: 1000:1
- A 4-degree per minute scan rate results in one full Earth-scan every 3 hrs

Resolution (m)	Aperture Size (cm)	Bandwidth (nm)	Scan Rate (deg/min)	Typical SNR
LAND: spectral radiance of 30W/(m ² micron sr), 562 nm center				
250	120	5	4	186
250	120	5	1	385
250	120	10	1	548
500	120	5	4	548
500	120	5	1	1097
500	240	5	4	1097
OCEAN: spectral radiance of 3.8W/(m ² micron sr), 551 nm center				
250	120	5	4	63
250	120	5	1	125
250	120	10	1	177
500	120	10	1	528



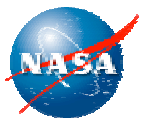
Preliminary Instrument Parameter Trades - 150 GSD

Wavelength(nm)	450	550	650	865
GSD(m)	150	150	150	150
optics transmission(6 surfaces)	$(.98)^6$	$(.98)^6$	$(.98)^6$	$(.98)^6$
obscuration factor	0.8	0.8	0.8	0.8
prism transmission	0.9	0.9	0.9	0.9
Spectral Bandwidth(nm)	5	5	5	5
Quantum Efficiency (QE)	0.8	0.87	0.85	0.8
% Full Area per 1hr	30	30	30	30
Integration Time(msec)	39	39	39	39
Ltypical radiance(W per m ² um Sr)	42 ocean	21 ocean	10 ocean	50 land (6 ocean)
Approximate SNR	650	531	394	985

Selected case by Science Team

Assumptions:

- 1.8m Aperture Diameter
- Disk Coverage to 40 degrees above the horizon, 3.07×10^9 pixels for 150m
- 1 hour time

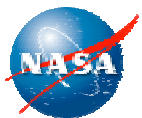


Selection of Instrument Parameters

- Coverage Data for 1 hr (2hrs - everything just doubles)
 - 5nm, 100mGDS, 650 SNR @450nm
 - 1. Given 650 SNR, 88ms -- 5.8% of full area
 - 2. Double BW to 10nm, 44ms -- 11.6%
 - 3. GSD 200m, 11ms -- 189%
 - 4. GSD 125m, 28ms -- 29%
 - 5. **GSD 150, BW to 5nm, 39ms --30% Selected Science Approach (45% for 1.5 hrs)**
 - 6. BW to 7.5nm, 26ms, GSD 150 --45%
 - 7. BW to 5nm, GSD 200m, 22ms -- 95%
 - 8. GSD 125m, 5nm, 56ms -- 15%
 - 9. GSD 125m, 7.5nm, 38ms -- 21%

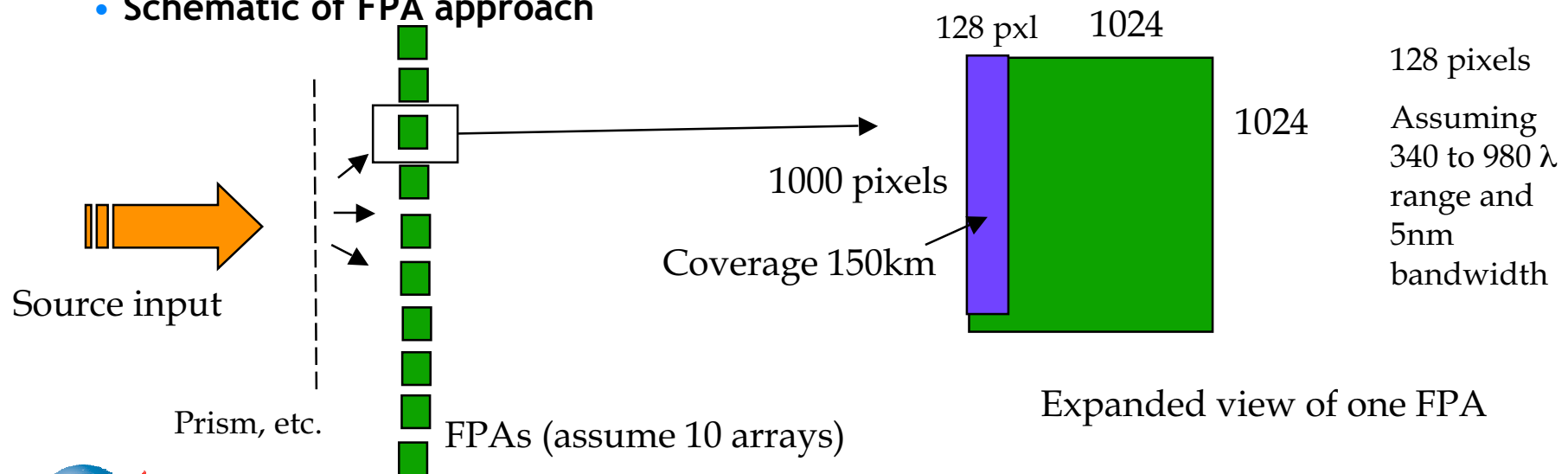
Assumptions:

- 1.8m Aperture Diameter
- Disk Coverage to 40 degrees above the horizon, 3.07×10^9 pixels for 150m
- 1 hour time



Instrument Implementation

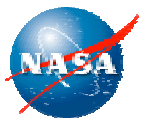
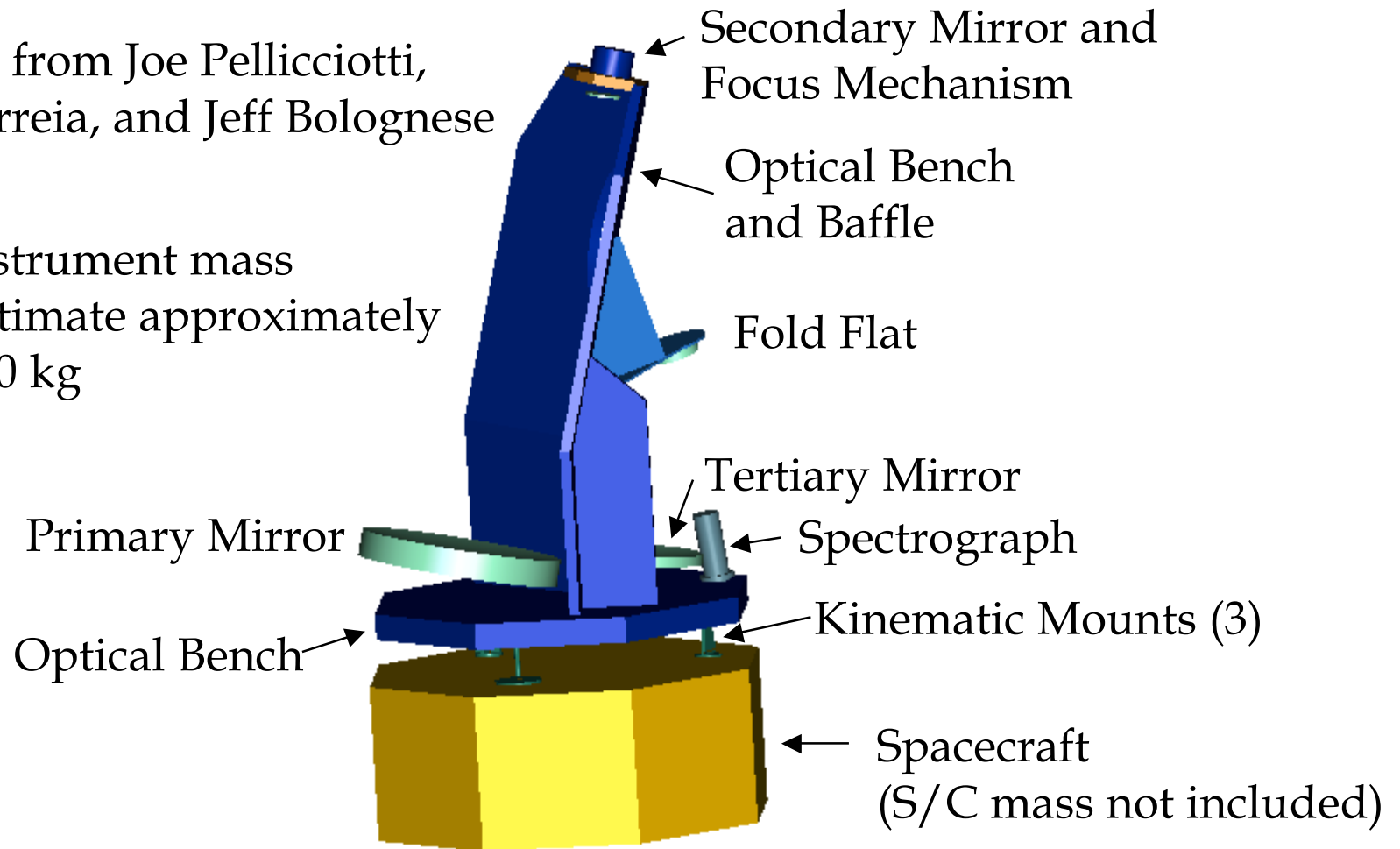
- **Pixels / Hr**
 - $10,000 \text{ pixels} \times 5400 \text{ sec} / .039 \text{ sec} = 14.2 \times 10^8 \text{ pixels per 1.5 hrs}$
- **Full Coverage**
 - $3.07 \times 10^9 \text{ pixels for 150m GSD}$
- **% Full Coverage**
 - $14.2 \times 10^8 \text{ pixels} / 3.07 \times 10^9 \text{ pixels} = \text{approx. } 45\%$
- **Bits / Sec**
 - $16 \text{ bits} \times 128 \times 1000 \times 10 / .039 \text{ sec} = 5.25 \times 10^8 \text{ bits/sec}$
- **Schematic of FPA approach**



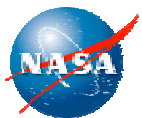
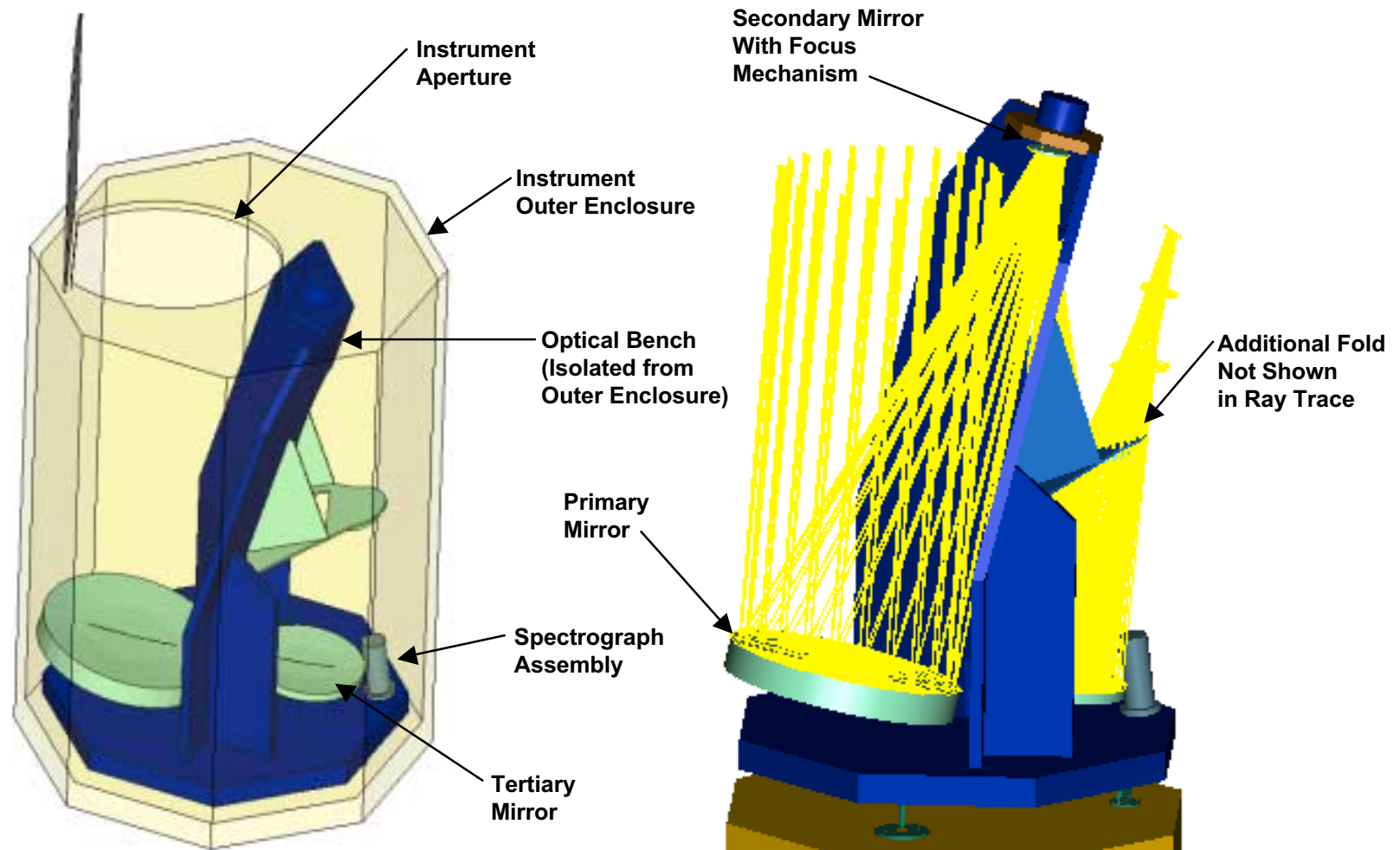
Instrument Diagram and Mass Estimate

Diagram from Joe Pellicciotti,
Mick Correia, and Jeff Bolognese

Instrument mass
Estimate approximately
800 kg



Instrument Detail Design Concept



Conclusions

- Science Approach selected:
 - GSD 150, BW to 5nm, 39ms, 45% of full coverage for 1.5 hrs

Wavelength(nm)	450	550	650	865
GSD(m)	150	150	150	150
optics transmission(6 surfaces)	$(.98)^6$	$(.98)^6$	$(.98)^6$	$(.98)^6$
obscuration factor	0.8	0.8	0.8	0.8
prism transmission	0.9	0.9	0.9	0.9
Spectral Bandwidth(nm)	5	5	5	5
Quantum Efficiency (QE)	0.8	0.87	0.85	0.8
% Full Area per 1hr	30	30	30	30
Integration Time(msec)	39	39	39	39
Ltypical radiance(W per m ² um Sr)	42 ocean	21 ocean	10 ocean	50 land (6 ocean)
Approximate SNR	650	531	394	985

- More study needed to refine and evaluate instrument implementation
- Preliminary study indicates that the mission is feasible.
- Several technology challenges remain:
 - Large (no. of pixels) and possibly complicated focal plane
 - Large, high quality optics - 1.8m lightweight mirror or alternate approach
 - Pixel digitization (16-bit, speed of readout)



Conclusions

- Preliminary study demonstrates both advantages and challenges of a GEO hyperspectral platform.
- Advantages are full diurnal hemispheric coverage of the Earth, or near-global coverage at a minimum rate of once every two days, all achievable with a single spacecraft.
- The challenge still remains to obtain desired high spatial and spectral resolution hyperspectral images with high SNR .
- EO-1: technology pathfinder
- EO-1 Hyperion data valuable for requirements studies and testing algorithms

